

PROGRESS IN SPECKLE-SHIFT STRAIN MEASUREMENT

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INTRODUCTION

The Instrumentation and Control Technology Division of the Lewis Research Center has been developing an in-house capability to make one-dimensional and two-dimensional optical strain measurements on high temperature test specimens. The measurements are based on the two-beam speckle-shift technique of I. Yamaguchi.¹ Past work has demonstrated 1-D and 2-D strain measurements at temperatures beyond 750° Celsius, with a resolution of 15-45 $\mu\epsilon$, respectively.²⁻³

The development of composite materials for use in high temperature applications is generating interest in using the speckle-shift technique to measure strains on small diameter fibers and wires of various compositions. This paper will cover the results of preliminary speckle correlation tests on wire and fiber specimens, and describe the Advanced System currently under development. Some of these results have been presented before, and are described in more detail in the reference.⁴

Past implementations of the speckle-shift technique used a linear photodiode array to detect objective speckle reflected from a point on a diffuse test surface. Shifts of this speckle pattern are proportional to surface strain along the incident plane of the optical system. A feature of the speckle shift technique is its ability to automatically cancel many problematic terms of rigid body motion. However, excessive rigid body

motions can move the reference speckle pattern off the one-dimensional detector, terminating the measurement. The advanced system now under development addresses two practical limitations encountered in previous testing. The first limitation was excessive decorrelation, due to off-axis rigid body motion shifts, restricting the magnitude of specimen movements. The speckle-shift technique could be applied to more diverse test situations, such as component testing, if the specimen mounting and loading requirements were not rigorous. The second limitation was the low sampling rate of the strain measurements, on the order of 0.1 Hz, limiting the response time of the system. Higher sampling rates would allow continuous loading at higher strain rates.

The use of a two-dimensional charge-coupled device (CCD) for the detector will reduce decorrelation errors due to rigid body motions. In addition, either a high speed image processing system, or a real-time data storage system is intended to greatly decrease the time between strain measurements. Two systems, each using one of these processing techniques, are currently being built.

THEORY

The laser speckle patterns, generated by the spatially coherent illumination of a rough specimen surface, shift when the surface is strained or when the specimen undergoes

rigid body motion. The speckle patterns are recorded on a sensor array, and cross-correlations of the patterns before and after movement are calculated to determine the amount of shift between them. A dual beam measurement allows automatic cancellation of most terms of rigid body motion. By taking the difference in shifts of speckle patterns generated by two laser beams incident on the specimen from equal but opposite angles, error terms due to rigid body motion can be cancelled.

The geometry of the optical setup and careful alignment of the specimen limit the speckle shifts to an axis parallel to the sensitive axis of the measurement system, namely, the incident plane of the laser beams; the speckle patterns remain correlated as long as they do not shift along the transverse direction, off the linear photodiode array.

The current system will allow one-dimensional strain to be measured at a rate near the data acquisition rate, by providing a two-dimensional digital signal processor (DSP) based speckle tracking processor. Rigid body motion constraints and decorrelation events will be reduced by using a two-dimensional CCD array to record an extended speckle pattern. A two-dimensional speckle pattern will allow off-axis speckle shifts to be tracked dynamically.

Figure 1 shows the simplified geometry of the coordinate system. The specimen is in the lowercase x,y plane, and the sensor is defined to lie in the uppercase X,Y plane. The x,y and X,Y planes are separated by a distance L_0 along the z axis. Two-dimensional deformation of object points on the specimen are described by vector $a(x,y)$, and the resulting shifts of the speckle pattern are given by vector $A(x,y)$. The shaded rectangle in the figure indicates a one-dimensional reference slice of the speckle pattern (one line of the 2-D CCD array) shifted from the origin by $A(x,y)$. The x,z plane is the plane of the incident laser beam, which comes from source point L_s .

After rigid body motion terms are cancelled out of the simplified speckle-shift equations, the surface strain ϵ_{xx} in the x direction can be calculated by the relation

$$\epsilon_{xx} = \frac{-\Delta A_x}{2L_0 \cdot \sin(\theta)} \quad (1)$$

where $\theta = |\theta_s|$, and ΔA_x is the difference between speckle shifts from beam 1 and beam 2

$$\Delta A_x = A_x(\theta_s) - A_x(-\theta_s). \quad (2)$$

An analysis of the optical system gave a measure of the minimum sampling frequency required by the CCD array to accurately represent the speckle patterns. By applying the Nyquist sampling theorem to the spatial frequency distribution of the speckle pattern, the minimum sampling frequency was calculated to be $8/\pi$, or 2.55 pixels/speckle.⁴

The optical system uses a switched single beam design, for compactness, following the schematic in Figure 2. The argon ion laser beam can be diverted into the beam stop by the acousto-optic modulator (AOM) between tests and exposures. The Pockels cell and polarizing beamsplitter form an optical switch, in order to provide the two beam paths for error cancellation. The Pockels cell can rotate the polarization of the beam by $\pi/2$ radians in accordance with a control signal. This allows the beam to either pass through the polarizing beamsplitter (beam leg 1) or be reflected to beam leg 2. A waist positioning achromatic lens is used to provide a planar wavefront at the specimen surface.

ROOM TEMPERATURE TESTS

When using a specimen of small thermal mass it is important not to induce local heating by the laser beam. This kind of heating causes thermal strain at the gage location, which contributes to speckle shifts. Since the shifts are due to real strain, they cannot be cancelled; they will consequently degrade any stress-strain relationship being measured.

When the room temperature tests were initially performed on wires, thermal strain was a problem at high laser power density levels. Once the laser output power was reduced from 2 W to $1/2$ W, however, the stability of the speckle patterns over succes-

sive exposures increased. For an incident power of 0.5 W and a 30 ms exposure time, the speckle patterns varied between a shift of zero and one pixel over a series of twenty exposures (about 20 minutes duration). Thermal strains were, therefore, negligible. The correlation function was sharply peaked over the duration of the test. Tungsten and stainless steel wires with diameters of 76 and 813 μm (3 and 32 mils), respectively, were used for these tests.

Correlations were also performed on speckle patterns from a variety of unloaded ceramic fiber specimens. The lower reflectivity of the ceramic fibers reduced the signal-to-noise level compared to the metallic specimens.

HIGH TEMPERATURE TESTS

One of the critical questions associated with high temperature optical measurements is whether thermal density gradients during a test are severe enough to prohibit accurate readings. Past testing has indicated problems of this sort at temperatures as low as 450°C. Free convection set up by air temperature and density variations around a hot specimen can result in an unstable phase propagation medium for the speckle-forming laser light. Since a stable speckle pattern depends explicitly on stable phase relationships, dynamic density variations can severely degrade the measurements.

If the density variations occur within a spatial extent smaller than a cross-section of the solid angle subtended between the laser spot on the specimen and the speckle pattern on the sensor, the speckle pattern will exhibit a boiling action. If, on the other hand, the phase medium varies on a scale larger than the cross-section of this solid angle the speckle pattern will jitter or vibrate as a field at the sensor. The latter case was observed during early testing.² In later testing³ the specimen was enclosed in a thermally insulating box. Subsequently, the jitter effect was not observed at test temperatures beyond 750°C.

Thermal effects of the first kind (boiling) cannot be compensated for if they exceed some minimum criterion necessary to maintain correlation between exposures.

However, the situation is different for speckle shifts due to thermal variations of the second kind, ie. those on a scale larger than the aforementioned solid angle. These shifts can be cancelled as rigid body motions if the shifted speckle pattern pair (one exposure from each beam) can be acquired fast enough to stop the relative movement of the thermal zone between exposures.

Further experiments were necessary to determine if the problem would recur at the much higher temperatures desired for future materials testing. An ac light bulb was used to provide a very hot wire specimen. The bulb provided a means of testing a tungsten alloy in an inert atmosphere using standard hardware. The glass envelope sealed the wire filament in dry nitrogen gas to prevent oxidation of the tungsten. The operating pressure in the envelope was estimated to be ≈ 1.5 atm. The envelope was transparent and cylindrical in shape (measuring 9 cm long by 3 cm in diameter), allowing the necessary optical access for the laser beams and speckle patterns. A variac was used to adjust the voltage across the filament without clipping the ac signal, effectively varying the filament temperature. A calibration of temperature versus line voltage was obtained from the bulb manufacturer.

The filament was made from a 37 μm (1.5 mil) diameter wire of W-Re alloy. The wire was tightly wound into a 122 μm (4.8 mil) diameter filament. The speckle statistics accurately obeyed those of a 122 μm diameter solid wire. A series of speckle patterns were recorded and correlated with a single pair of reference patterns at a specimen temperature of 2480°C. Excellent stability was observed in the high temperature tests, indicating that the isolation provided by the glass envelope was sufficient to avoid thermally induced jitter. The correlation peak occurred at shift values of 0 and 1 pixels over time, which is within the resolution of the correlation algorithm. Figures 3.a and 3.b show a set of reference and shifted speckle patterns, and their correlation over a shift range of ± 60 pixels. The patterns were recorded using a linear photodiode array camera. Since the wire was subjected to neither load nor rigid body motion, there should be no offset between the patterns. Indeed, the correlation in

Figure 3.b is sharply peaked at an offset of zero, as expected. The speckle pattern stability was also very good at room temperature and 1825°C. A radiometric analysis of a typical test system shows that optical signals can be measured at temperatures around 3000°C.⁴ These results alone do not guarantee accurate measurements at high temperatures using a straight wire specimen. Acquisition of the speckle pattern pairs must always occur fast enough to stop the action of any translations of the specimen or changes in the strain state at the gage position introduced by the test apparatus.

ADVANCED SYSTEM REQUIREMENTS

The Advanced System effort concentrates on developing a one-dimensional strain measurement system capable of calculating strains from speckle pattern shifts using a high speed digital signal processor (DSP). The system will provide the abilities to continuously track on-axis and off-axis speckle movements from a stressed wire specimen, and measure the induced strain. The ability to track the reference speckle patterns when off-axis speckle movements occur diminishes decorrelation effects and increases the measurement range of the instrument. In addition, the alignment criteria for the test specimen will not be as stringent, and less specialized load apparatus can be used for the tests.

Two versions of a speckle tracking system are under development. One technique uses a high speed personal computer with a digital signal processor (DSP) to process strain data as it is acquired (concurrent processing). The concurrent processing system development emphasizes minimizing the amount of data transferred to the PC, and then calculating the strain quickly before acquiring new data. The second technique stores the speckle data for processing after the test run (post-processing), allowing potentially higher strain rates. The post-processing approach stores all of the incoming speckle data, in real time, for the duration of the test run. The strains are then calculated once the run is completed.

In both systems, full field speckle patterns

will be recorded electronically as the specimen undergoes strain and rigid body motions. When the speckle pattern shifts off the primary viewing axis during a run, the reference slice (the center video line of the unshifted speckle pattern) will still be somewhere on the two-dimensional sensor array and correlation can be maintained. It will be necessary to perform a number of correlations per strain point to track the speckle shifts. The reference speckle patterns must be correlated with video lines on the array both above and below the reference axis coordinate. This is essentially a limited two-dimensional correlation. The speckle tracking algorithm will search for a correlation peak in each video frame until some minimum confidence criterion is met. The coordinates of this correlation peak give the shift components along the sensitive strain axis as well as the transverse axis. In addition to finding the coordinates of the correlation peak, the DSP-based image processor will automatically update the reference patterns before decorrelation occurs, allowing a virtually unlimited range of strain and rigid body motion shifts.

CONCLUSIONS

An analysis of the optical considerations involved in speckle-shift strain measurements on high temperature wire or fiber specimens is reported. The speckle patterns generated by a highly asymmetric laser spot are suitable for a one-dimensional strain measurement. The minimum sampling interval of the CCD detector is 2.55 pixels/speckle. A radiometric analysis indicates that a speckle pattern should be visible using extended specimens at temperatures below about 3000°C.

Preliminary high temperature testing showed that stable objective speckle patterns can be recorded from a tungsten filament at 2480°C. The gas immediately surrounding the filament was enclosed by a thin glass envelope. Good speckle patterns are obtainable at room temperature from small diameter (~100 μ m) ceramic fibers, without the laser inducing noticeable local heating of the test section.

A high speed optical strain measurement

effort is in progress, which will be able to track moving speckle patterns in two dimensions. This high speed tracking ability will allow the speckle-shift technique to be used in more diverse test environments.

REFERENCES

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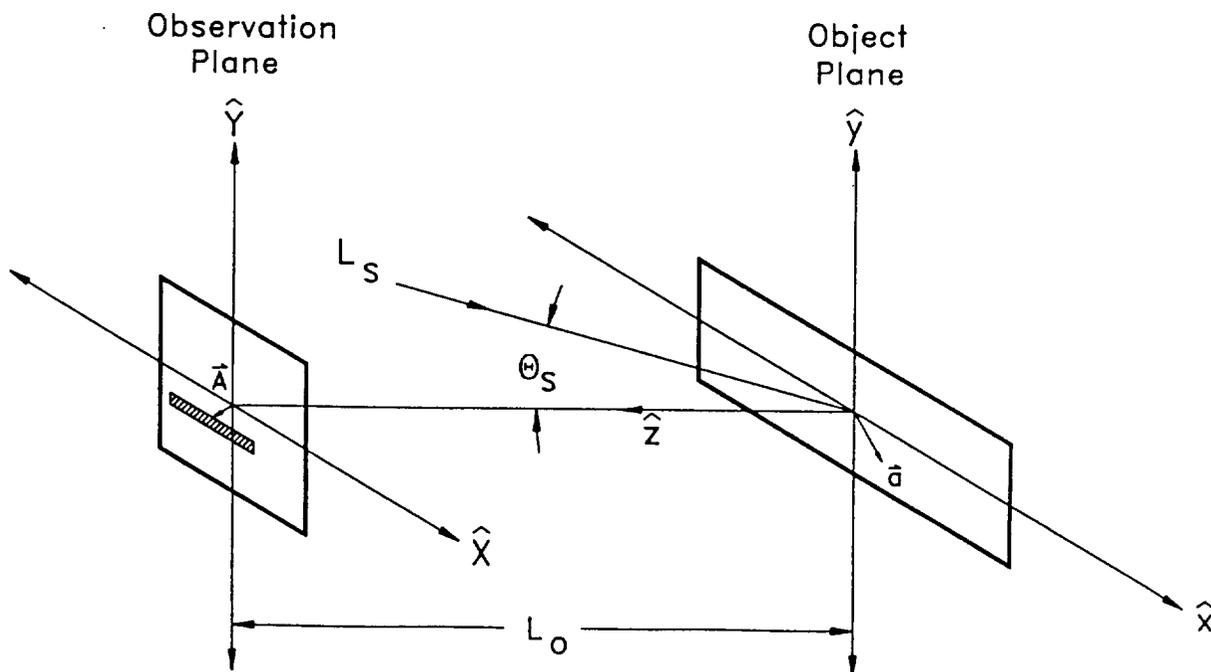


Figure 1. - Simplified coordinate system.

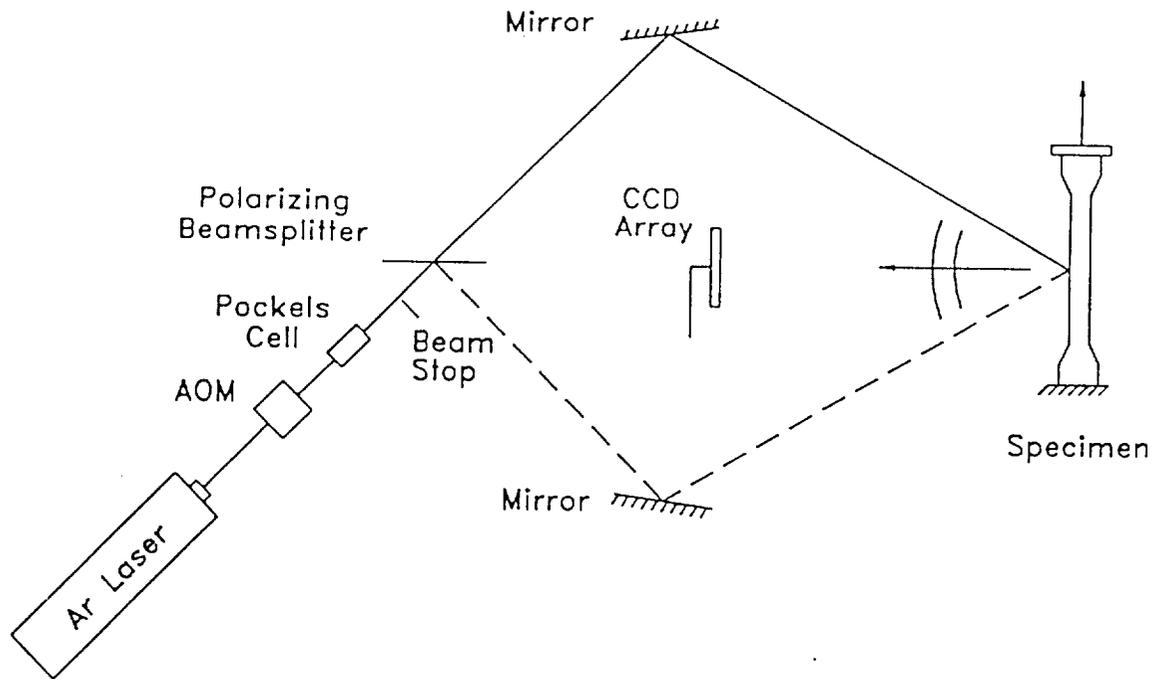
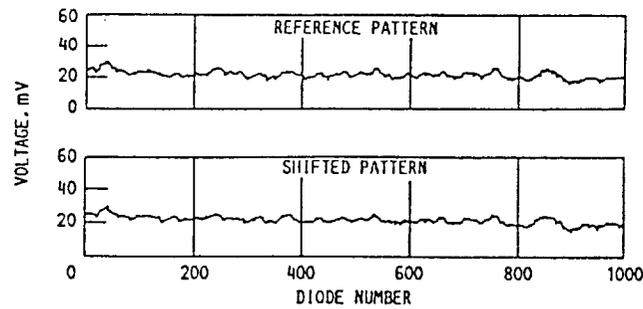
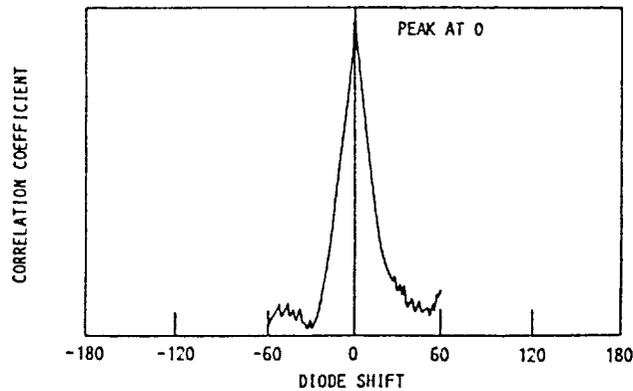


Figure 2. - Optical schematic.



(a) REFERENCE AND SHIFTED SPECKLE PATTERNS.



(b) CORRELATION.

Figure 3. - Typical speckle pattern pair and their correlation, for a tungsten wire at 2,480 °C.